# Composite Bosonic Dark Matter

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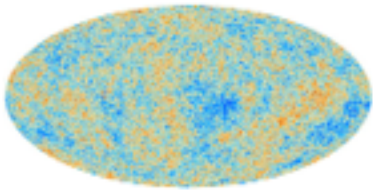
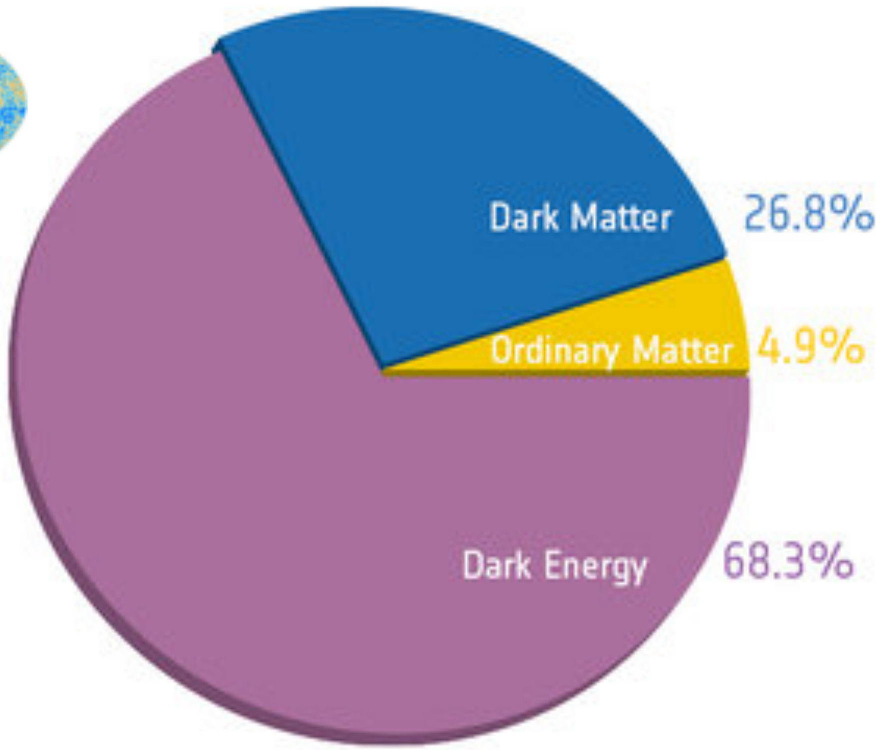
[LSD Collaboration]
RBRC Lunch Seminar
December 12, 2013

# Motivation - the dark universe

- Our universe is mostly dark! Substantial evidence for dark matter (galactic rotation, gravitational lensing, large-scale structure.)

- No obvious connection between DM and ordinary matter (SM) except gravity…so why is there roughly the same amount of each?

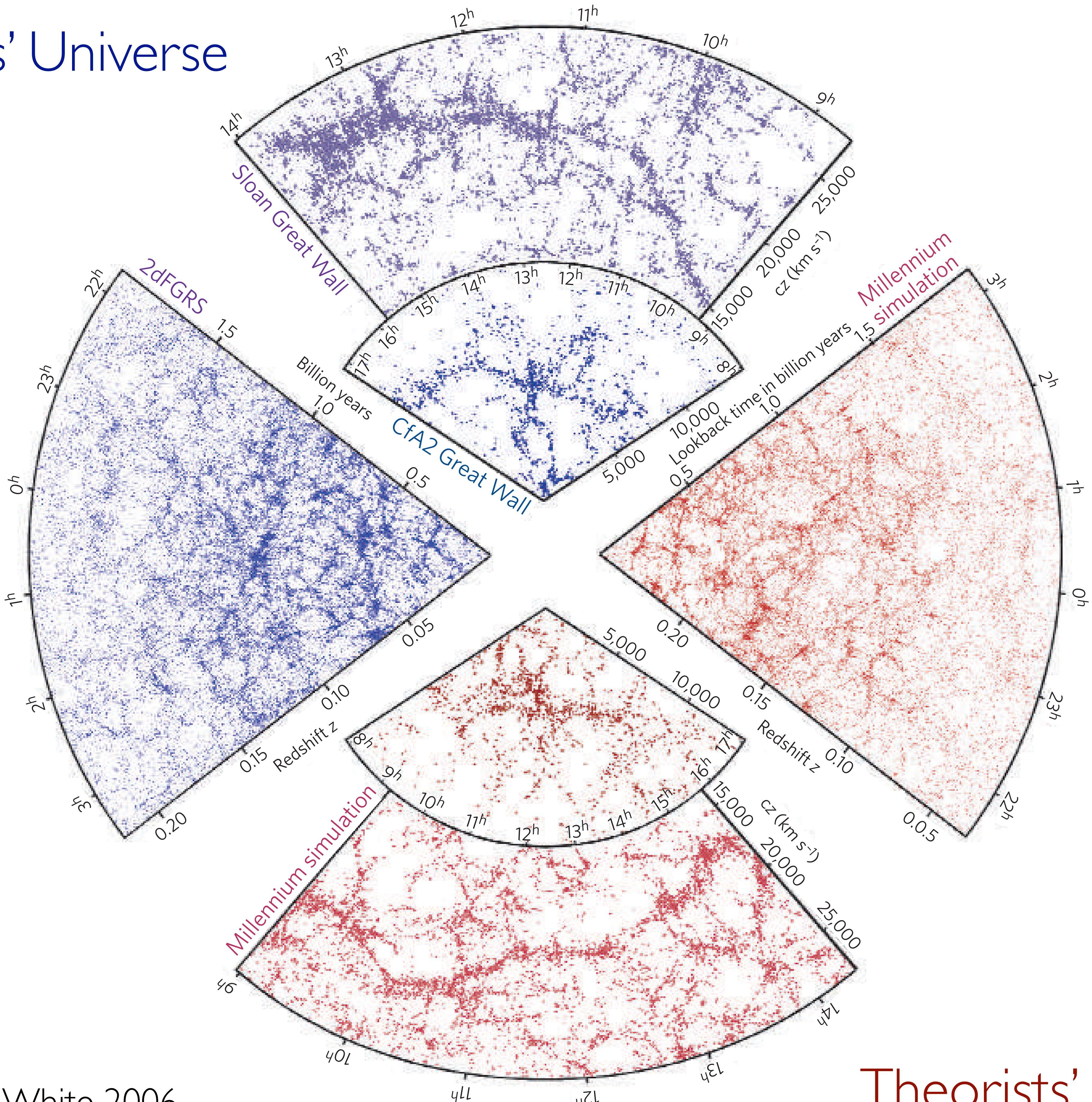





(today)

**(borrowed from slides by Mike Boylan-Kolchin)**

# Observers' Universe

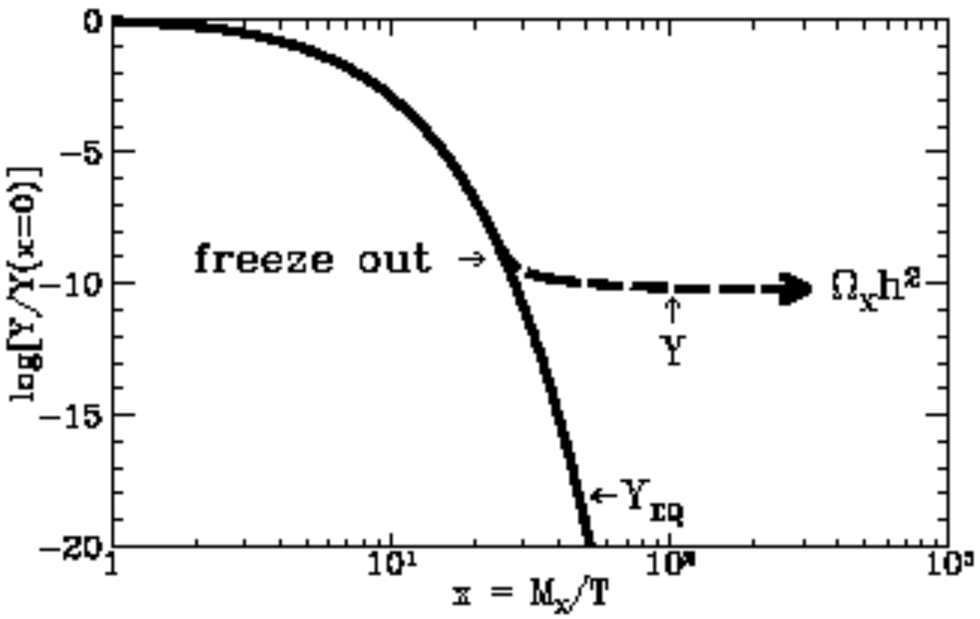



# Theorists' universe

Springel, Frenk, White 2006

# Dark matter relic density

http://ned.ipac.caltech.edu/level5/Kolb/Kolb5_1.html

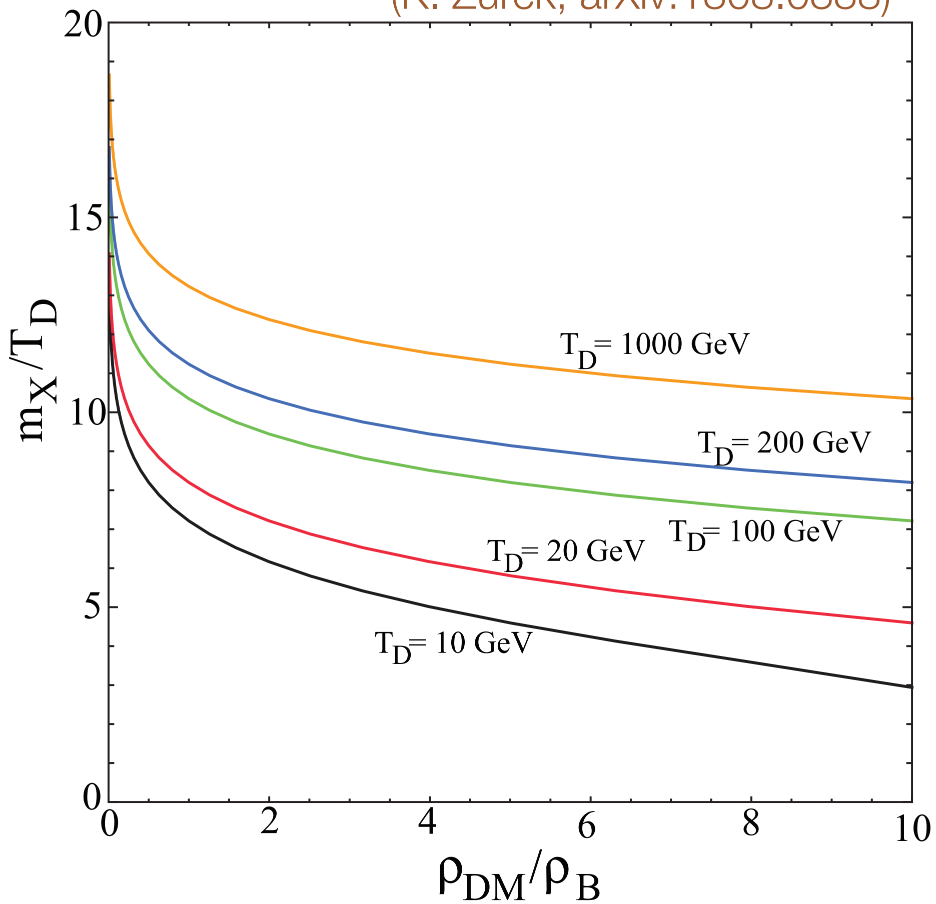



- Dark matter could be a thermal relic (WIMP miracle):

$$\langle \sigma v \rangle_{\text{ann}} \sim 1 \text{ pb} \sim \frac{\alpha^2}{(100 \text{ GeV})^2}$$

- Requires interaction w/SM heat bath!

(K. Zurek, arXiv:1308.0338)



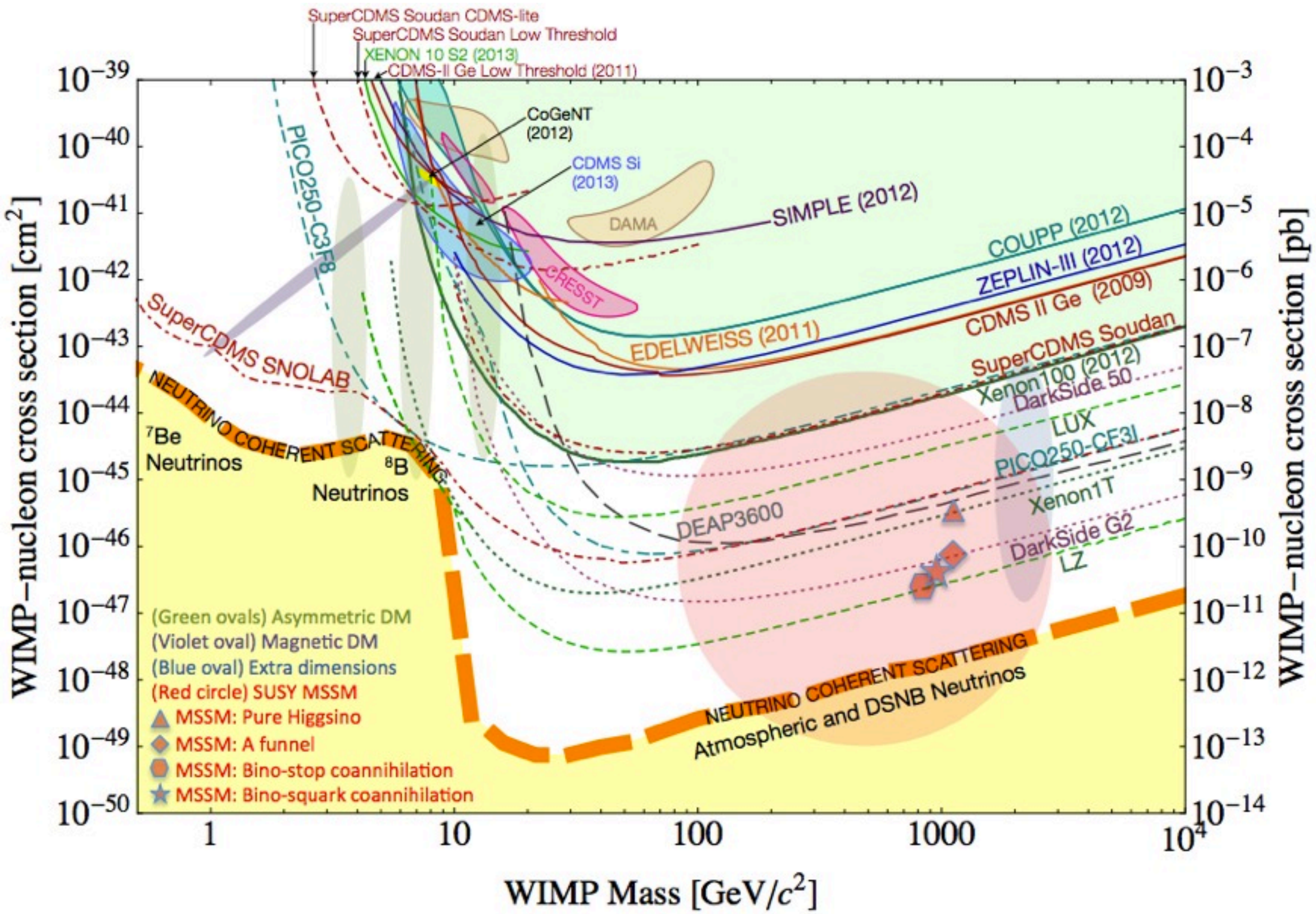

- Dark matter could arise from a primordial asymmetry:

$$n_\ell - n_{\bar{\ell}} \sim n_b - n_{\bar{b}} \sim n_D - n_{\bar{D}}$$

- Once again, coupling to SM in early universe essential. (Strong self-coupling to wash out thermal relic helps too!)

# Putting the "dark" in dark matter

- Most obvious scenarios ruled out long ago (e.g. the WIMP can't actually exchange Z bosons at tree level - $10^{-38}$ xsec.)
- Asymmetric scenarios tend to favor light DM, where sensitivity is lower, but still constrained. Important to look everywhere we can, though!

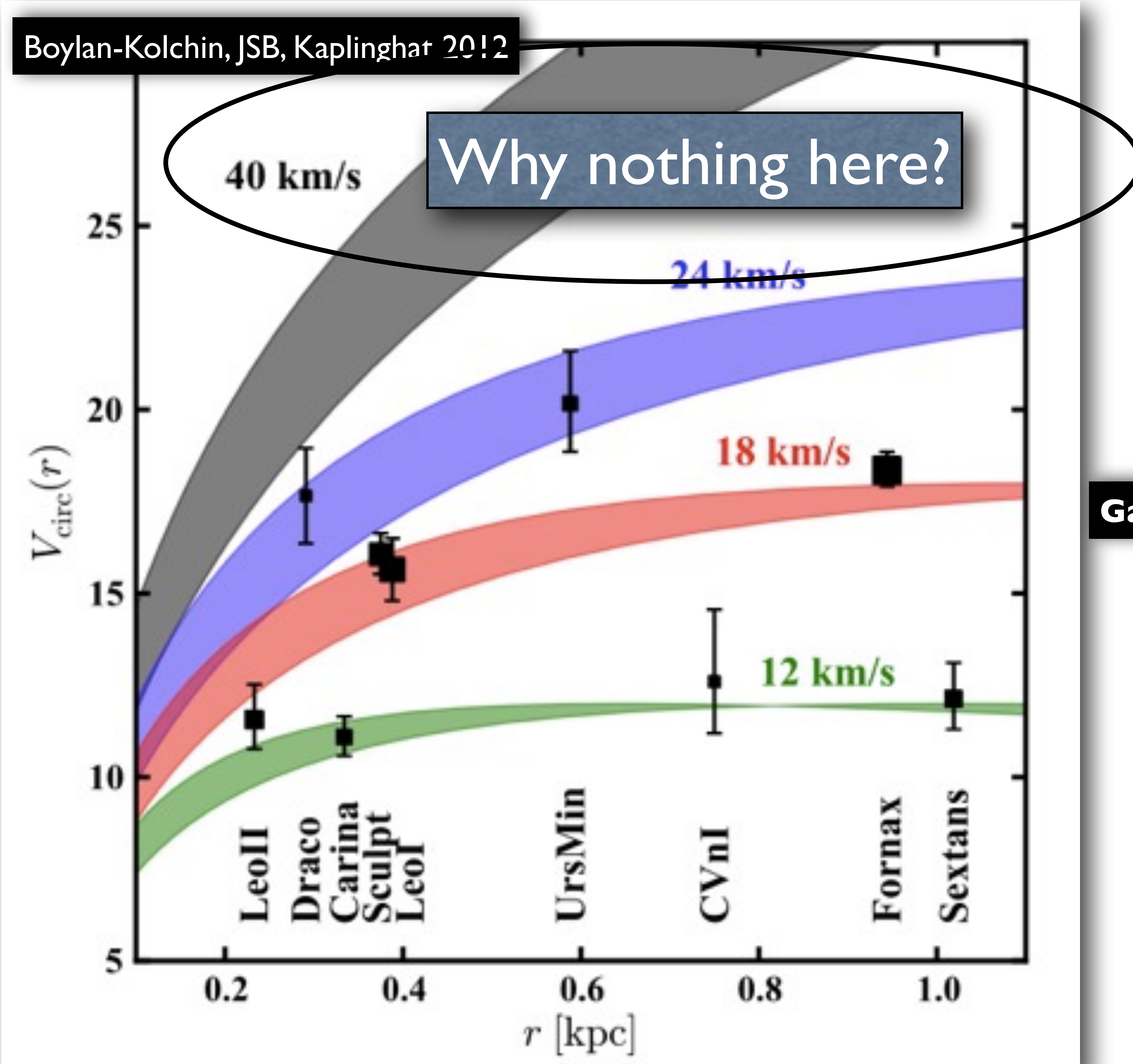



(from talk by B. Edwards, LME 2013 workshop)

# Self-interacting dark matter

- Cold, collisionless DM paradigm is great at large-scale structure, but has problems explaining behavior of dwarf galaxies (DM-dominated)
- "Core vs. cusp": observed velocity distribution of dwarf galaxies points to less DM abundance in center of galaxy than expected from simulation (cored profile)
- "Missing satellites": Not enough dwarf galaxy satellites seen around the Milky Way (and the missing ones are the most massive expected!)
- Strongly self-interacting DM can resolve these problems without affecting large-scale structure! Need cross section around $0.5\ \mathrm{cm}^2/\mathrm{g}$ (a **barn** for GeV dark matter!!)

# Summary of the Too Big To Fail problem:



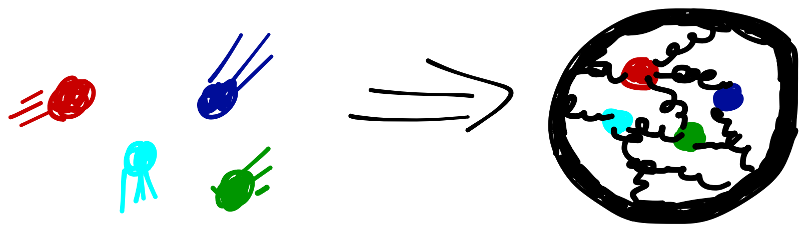

Expect 5-40 subhalos with $V_{max}$ >25 km/s

(from 44 simulations)

Garrison-Kimmel et al. in prep

# Composite dark matter

- Many solutions, but one well-motivated option is composite dark matter - specifically, DM as a strongly-bound state of some more fundamental objects

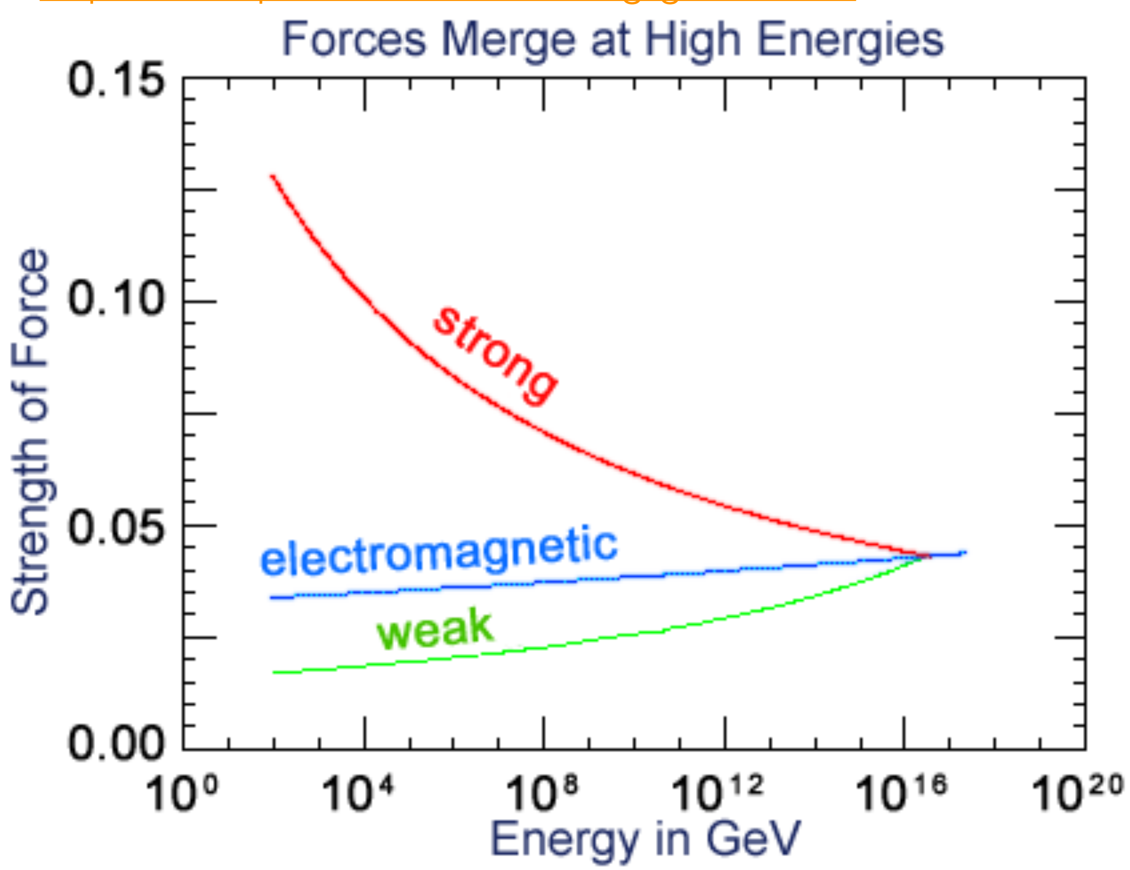


- Fundamental particles can carry tree-level SM charges, be active in early universe, then confined today

- Inspiration from neutron of QCD ("rescaling" QCD and messing with some of the parameters gives a stable, neutral baryon.)

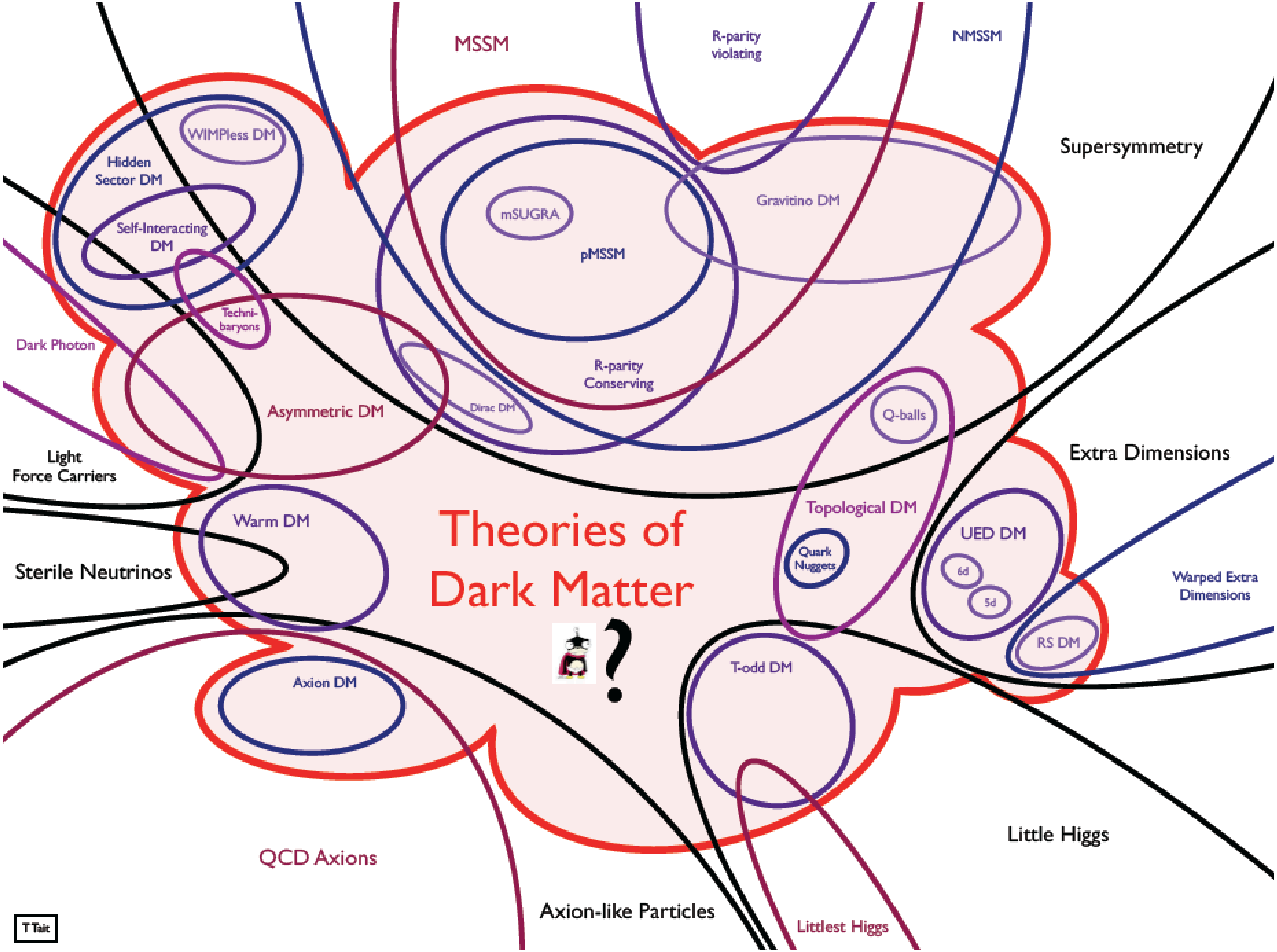
# How ad-hoc is this, anyway?

http://www.particleadventure.org/grand.html




- Composite Higgs theories usually give rise to dark matter that looks like this (analogue of baryon number)
- Also, decoupled dark gauge sectors can appear as hidden sectors arising from GUT or string-inspired models.
- This isn’t the weirdest DM candidate model out there…

(borrowed from T. Tait)



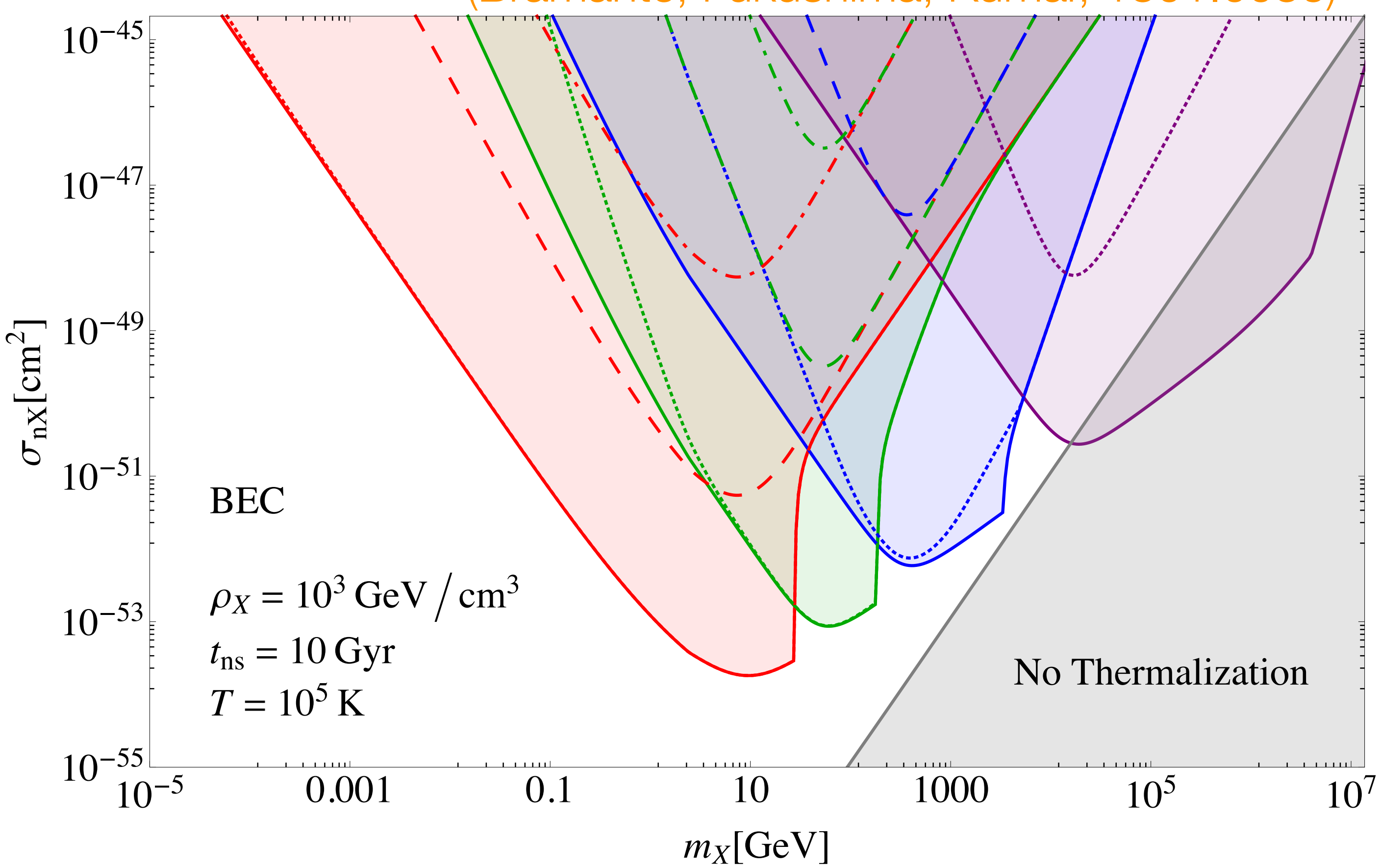
# Bosonic dark matter

- Why study composite bosonic dark matter, in particular?
- "Because it's there" - plenty of strongly-coupled theories where baryon-like states contain even number of fermions. In this talk: SU(4) gauge theory.
- Different phenomenology - operators in effective theory for e.g. direct detection are somewhat different (I'll come back to this in detail.)
- Other astrophysical consequences…?

# Dark matter and the fate of neutron stars

- Oldest neutron stars seen ~10 Gyrs. Constraint on bosonic DM, which can accumulate and cause collapse to black hole (especially if BEC forms!)
- Self-interaction/annihilation reduce DM density and weaken bounds
- For a strongly-coupled dark sector both the QCD and DM interiors of the neutron star could be in exotic states…

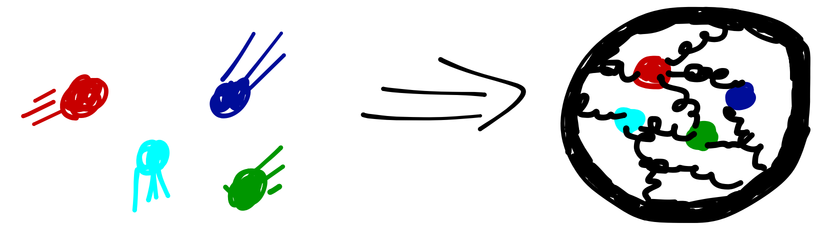
(Bramante, Fukushima, Kumar, 1301.0036)




- Exotic neutron star cores with color superconducting quark matter and no electrons give rise to very large thermalization times which protects neutron stars from their possible destruction as a result of DM accretion. Hence the discovery of asymmetric, bosonic DM could motivate the existence of exotic neutron star cores.

(Bertoni, Nelson, Reddy, 1309.1721)

# Four-color DM: the basic idea



- SU(4) with some fundamental-representation fermions. Similar enough to QCD that our intuition should help. Simplest such theory with bosonic DM candidate (also SU(2), but enhanced chiral symmetry makes it weird - see my BNL talk from April)

- 4 is large enough that we can use large-$N_C$ for some predictions, at least to start. It's also small enough that we can do lattice simulations practically.

- We consider the model in isolation from EW symmetry breaking, for maximum generality. but insights here could be incorporated into a composite Higgs model.

- Model work in progress, mainly with Graham Kribs and Mike Buchoff.

# Fermion content and charge assignments

- Motivation: minimal set of fermions to allow coupling to SM electroweak, including Higgs boson. Need $SU(2)_L$ doublet + singlets.

| Field | $\mathrm{SU}(4)_D$ | $(\mathrm{SU}(2)_L,\, \mathrm{SU}(2)_R)$ |
|---|---|---|
| $F_1$ | $\mathbf{4}$ | $(\mathbf{2}, \mathbf{1})$ |
| $F_2$ | $\bar{\mathbf{4}}$ | $(\bar{\mathbf{2}}, \mathbf{1})$ |
| $F_3$ | $\mathbf{4}$ | $(\mathbf{1}, \mathbf{2})$ |
| $F_4$ | $\bar{\mathbf{4}}$ | $(\mathbf{1}, \bar{\mathbf{2}})$ |

- Choose to impose $SU(2)_R$ global as well; embed hypercharge as shown. Leaves custodial SU(2) to suppress contributions to precision EW, etc.

$$Y = T_{3,L} + T_{3,R}$$

- Most general mass matrix allows both vector-like and Yukawa mass terms.

$$\mathcal{L} \supset m_{12} F_1 F_2 + m_{34} F_3 F_4 + h.c.,$$

$$\mathcal{L} \supset y_{14} F_1 H F_4 + y_{23} F_2 H^\dagger F_3 + h.c.$$

- Set Yukawas equal and stack into Dirac spinors:

$$\psi_L \equiv \begin{pmatrix} F_1 \\ F_2^\dagger \end{pmatrix}, \psi_R \equiv \begin{pmatrix} F_3 \\ F_4^\dagger \end{pmatrix}$$

# Fermion mass matrix

- Mass matrix to be diagonalized:

$$\mathcal{L} \supset (\bar{\psi}_L \bar{\psi}_R) \begin{pmatrix} m_{12} & yv \\ yv & m_{34} \end{pmatrix} \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$$

- Can be done with one real mixing angle: $(\Delta \equiv m_{34} - m_{12})$

$$\sin^2\theta = \frac{1}{2}\left(1 - \frac{\Delta}{\sqrt{4y^2v^2 + \Delta^2}}\right) \qquad M_\pm = \frac{1}{2}\left(m_{12} + m_{34} \pm \sqrt{4y^2v^2 + \Delta^2}\right)$$

- Vacuum alignment is a concern (we don't want to break EW symmetry appreciably at a higher scale!) Work in progress, but for now focus on EW-preserving limit,

$$yv \ll m_{12}, m_{34}$$

# Lattice Strong Dynamics Collaboration

James Osborn

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Oliver Witzel
Evan Weinberg

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Sergey Syritsyn

Meifeng Lin

Graham Kribs

Evan Berkowitz
Enrico Rinaldi
Chris Schroeder
Pavlos Vranas

Joe Kiskis

David Schaich

Tom Appelquist
George Fleming
Gennady Voronov

Mike Buchoff

# Lattice simulation details

- Simplest approach to start: unimproved Wilson fermions, plaquette action
- All results so far are quenched (no fermion loops.)  Studying heavy fermions and larger Nc, so should result in smaller errors than quenching QCD.
- Implemented using the Chroma code base - 2c/4c merged back into public repository

**Nucl.Phys. B225 (1983) 156 Results**

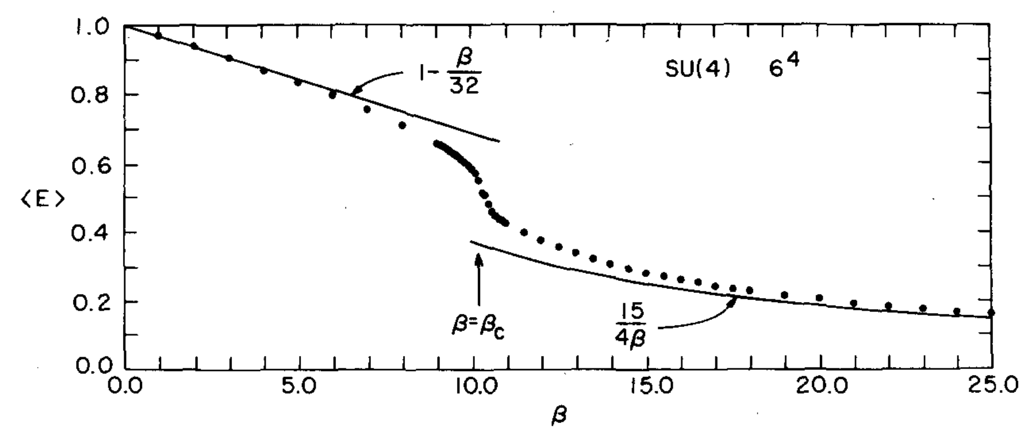
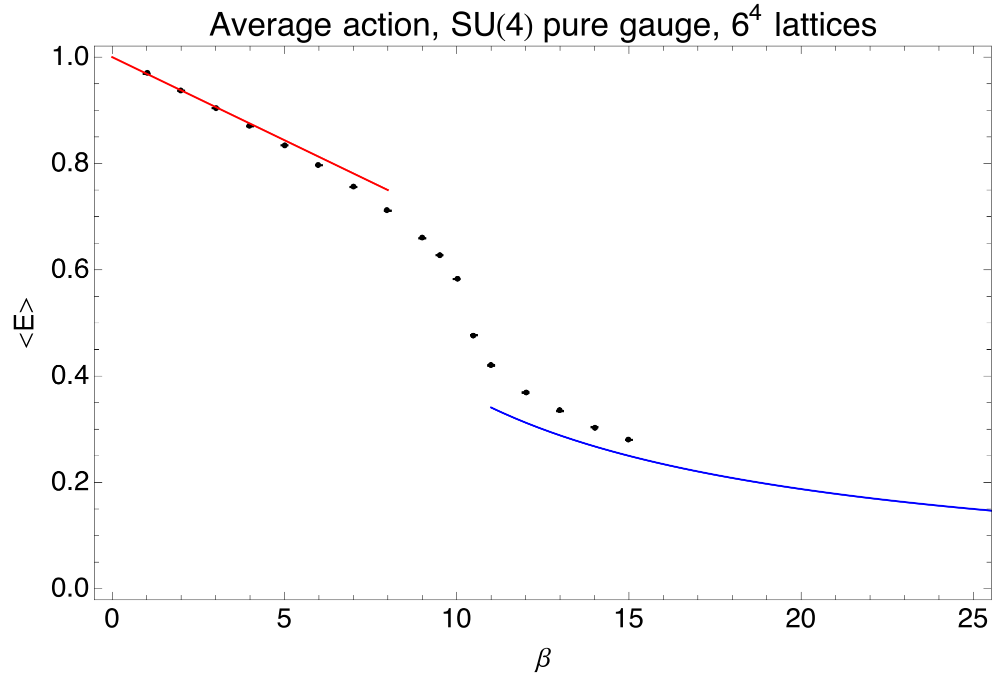



Fig. 10. The average action per plaquette $\langle E \rangle$ for pure SU(4) gauge theory on a $6^4$ lattice as a function of the inverse temperature $\beta$. The curves represent the leading-order high- and low-temperature expansions of eqs. (1) and (3), respectively.

## Our Code

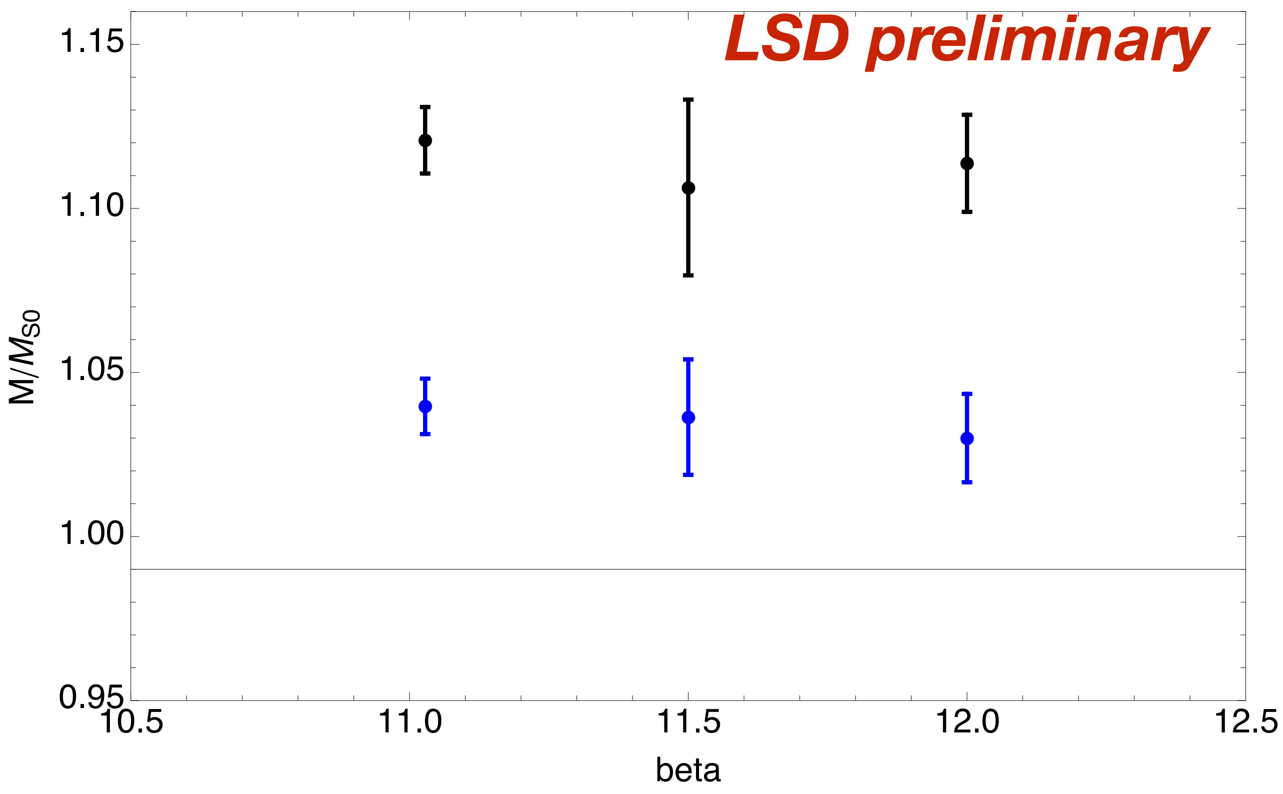


# Set of ensembles

| $N_c$ | $\beta$ | $\kappa$ | $N_s^3 \times N_t$ | # Meas. |
|---|---|---|---|---|
| 4 | 11.028 | 0.1554 | $16^3 \times 32$ | 4878 |
| | | | $32^3 \times 64$ | 1126 |
| | | 0.15625 | $16^3 \times 32$ | 4765 |
| | | | $32^3 \times 64$ | 1146 |
| | | | $48^3 \times 96$ | 1091 |
| | | 0.1572 | $32^3 \times 64$ | 1075 |
| | 11.5 | 0.1515 | $16^3 \times 32$ | 2975 |
| | | | $32^3 \times 64$ | 1057 |
| | | 0.1520 | $16^3 \times 32$ | 2872 |
| | | | $32^3 \times 64$ | 1052 |
| | | 0.1523 | $16^3 \times 32$ | 2976 |
| | | | $32^3 \times 64$ | 914 |
| | | | $48^3 \times 96$ | 637 |
| | | | $64^3 \times 128$ | 489 |
| | | 0.1524 | $16^3 \times 32$ | 2970 |
| | | | $32^3 \times 64$ | 863 |
| | | 0.1527 | $32^3 \times 64$ | 1011 |
| | 12.0 | 0.1475 | $32^3 \times 64$ | 1125 |
| | | 0.1480 | $32^3 \times 64$ | 1189 |
| | | 0.1486 | $32^3 \times 64$ | 1055 |
| | | 0.1491 | $16^3 \times 32$ | 411 |
| | | 0.1491 | $32^3 \times 64$ | 1050 |
| | | 0.1491 | $48^3 \times 96$ | 1150 |
| | | 0.1491 | $64^3 \times 128$ | 928 |
| | | 0.1495 | $32^3 \times 64$ | 1043 |
| | | 0.1496 | $32^3 \times 64$ | 1009 |
| 3 | 6.0175 | 0.1537 | $32^3 \times 64$ | 1000 |
| | | 0.1547 | $32^3 \times 64$ | 1000 |

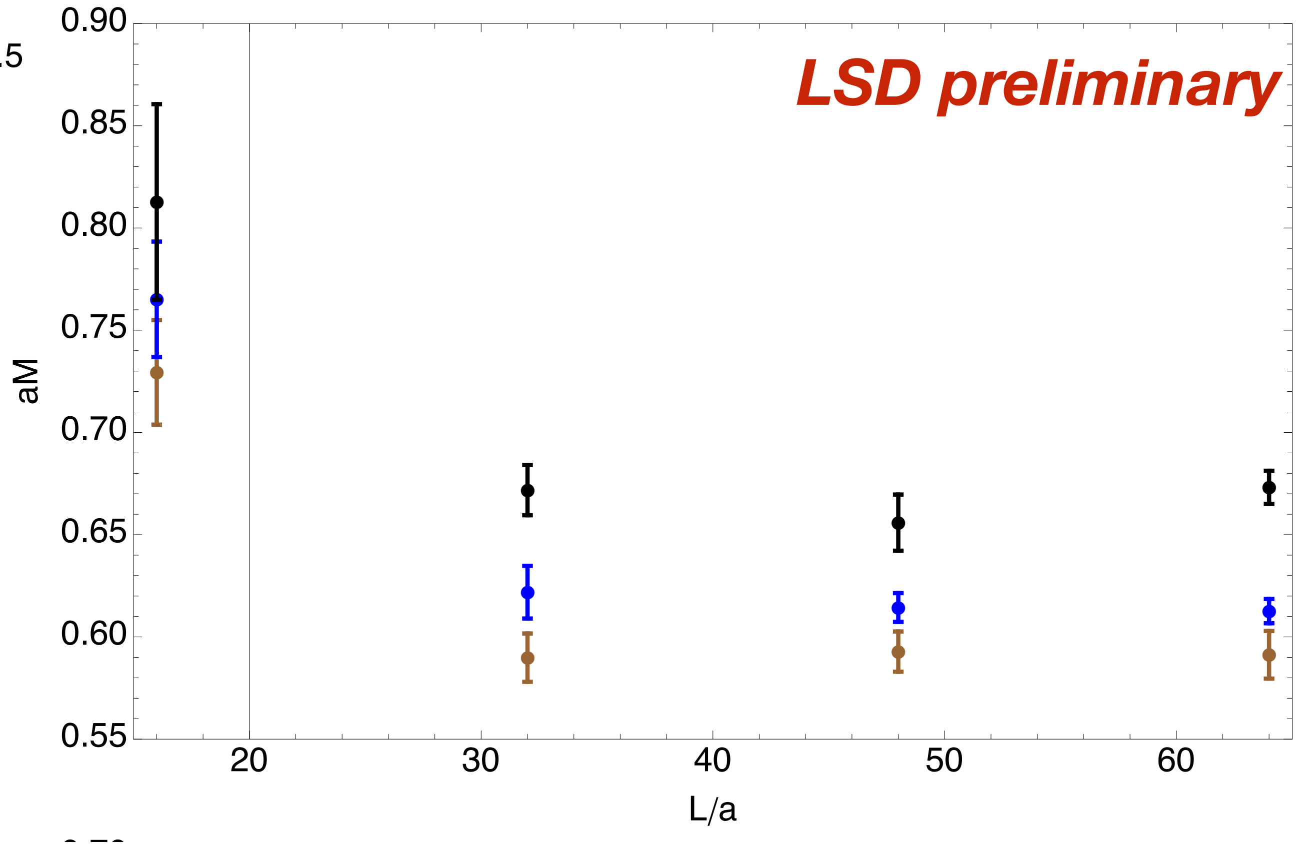
- Quenching allows huge volumes!
- 3-color lattices matched for comparison (string tension)
- All measurements with two valence fermions (we assume splitting between vector-like masses.)

# Study of systematic effects



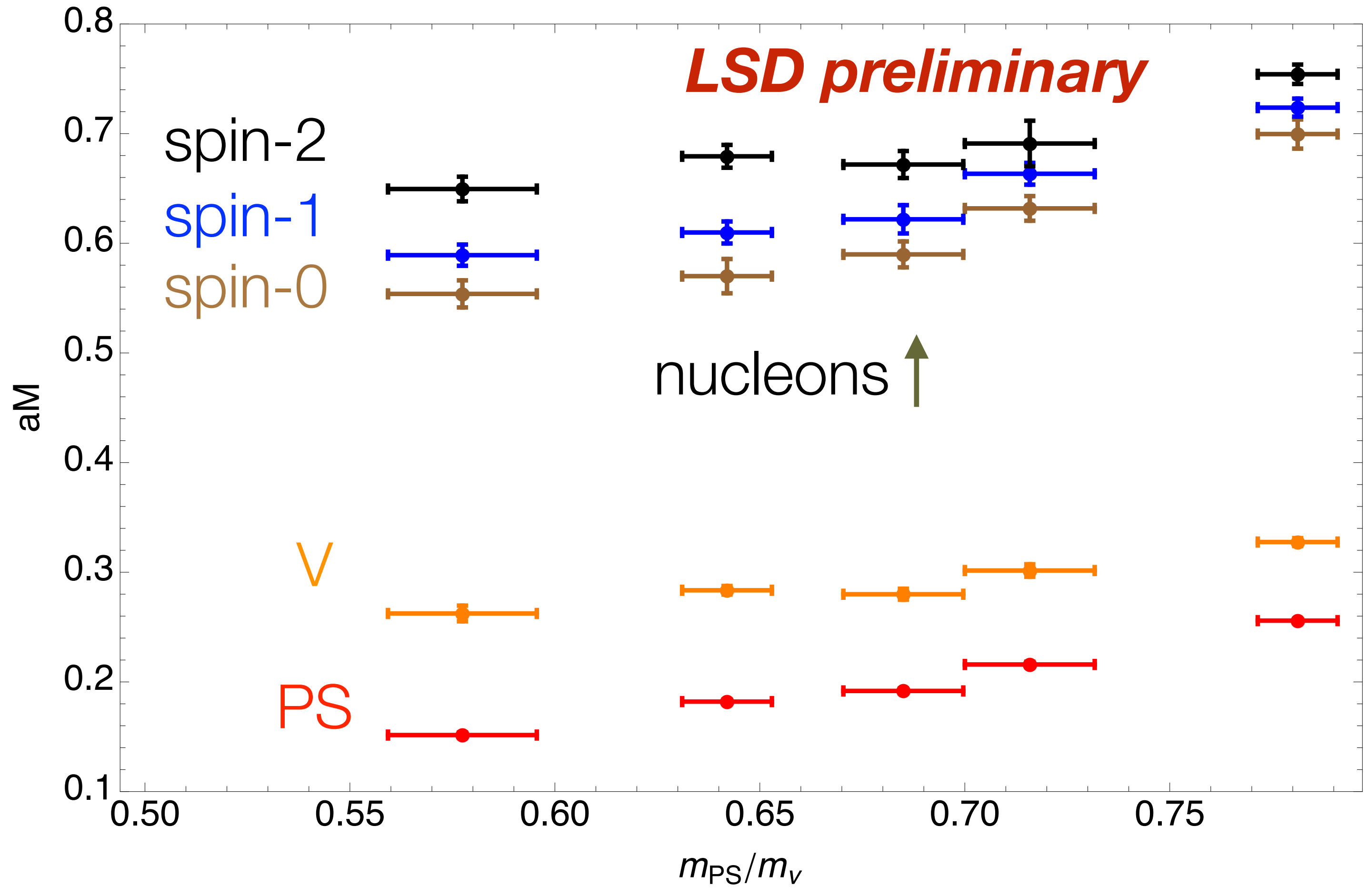

Cutoff effects

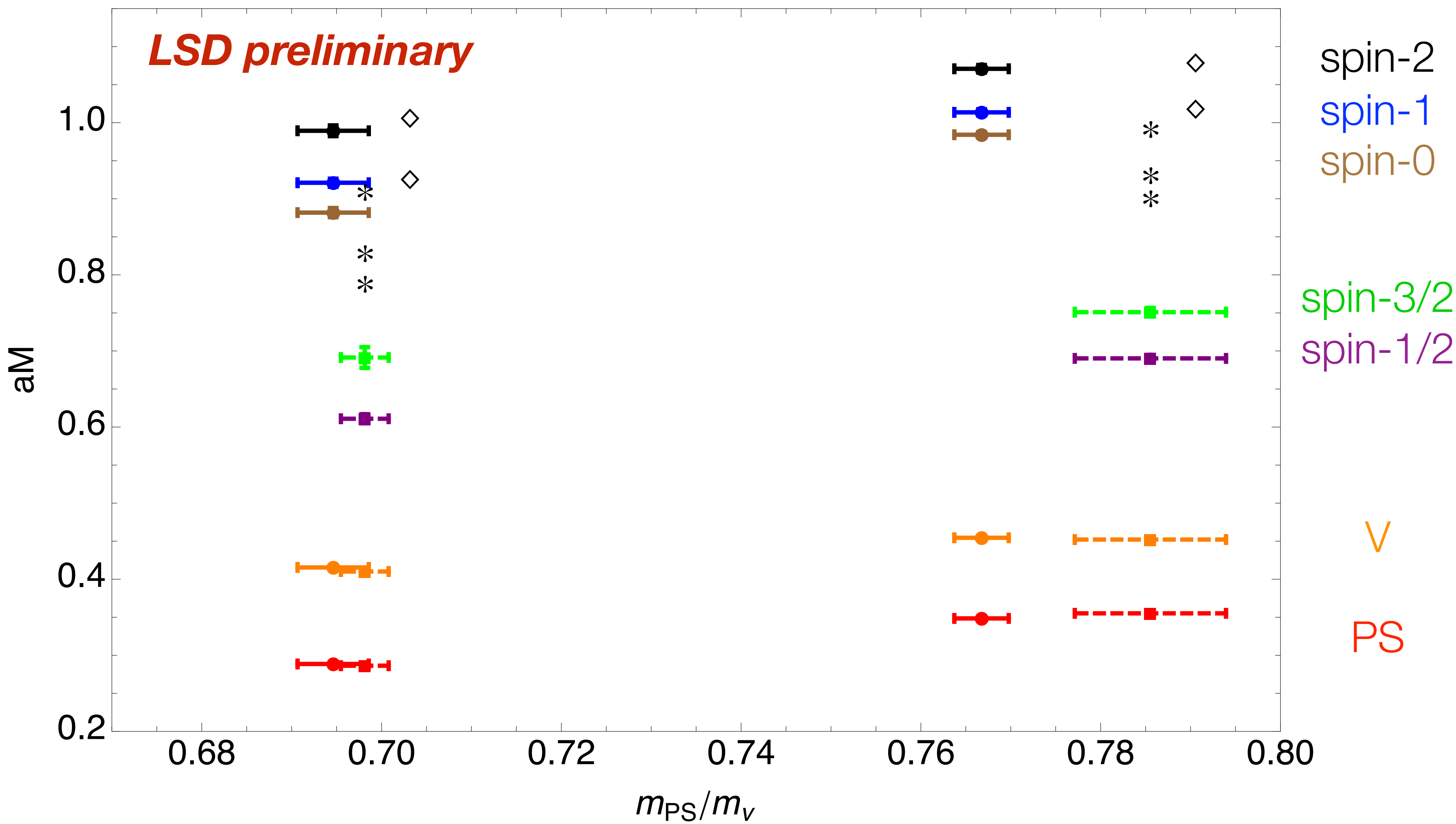
Finite-volume effects



# Spectrum

- Spectrum scaling with input mass shown right.
- Study of splitting masses in the immediate future… is there a corner of the space where the spin-1 baryon is lightest?






$$* : \quad M(N_c, J) = N_c m_0 + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

$$\diamond : \quad M(N_c, J) = N_c m_0^{(0)} + C + \frac{J(J+1)}{N_c} B + \mathcal{O}(1/N_c^2)$$

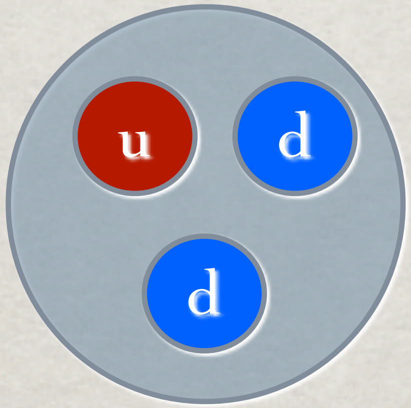
(slide courtesy of M. Buchoff)

# Baryon Flavor Symmetry

Invariant under $SU(N_f)$ transformations

★ Flavor Non-symmetric

Example: (3-color neutron ala QCD)



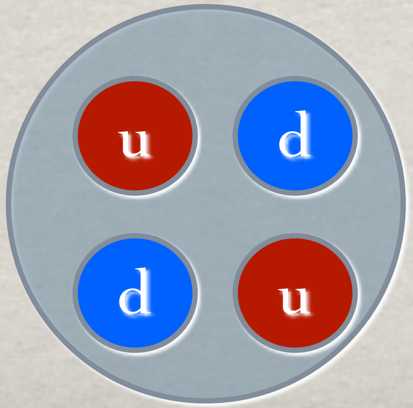

$$Q_u = Q_d$$

or

$$Q_u \neq Q_d$$

★ Flavor Symmetric

Example: (4-color neutron)




$$Q_u = -Q_d$$

only

(slide courtesy of M. Buchoff)

# How we might see it?

| | Dim-5<br>$\overline{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$<br>Magnetic Moment | Dim-6<br>$(\overline{\psi}\psi)v_\mu\partial_\nu F^{\mu\nu}$<br>Charge Radius | Dim-7<br>$(\overline{\psi}\psi)F_{\mu\nu}F^{\mu\nu}$<br>Polarizability |
|---|---|---|---|
| Odd Nc<br>No baryon flavor sym. | ✓ | ✓ | ✓ |
| Odd Nc<br>Baryon flavor sym. | | | ✓ |
| Even Nc<br>No Baryon flavor sym. | | ✓ | ✓ |
| Even Nc<br>Baryon flavor sym. | | | ✓ |

# Direct detection: EM polarizability

- Naive first estimate: use neutron EM polarizability from PDG, assume naive scaling w/mass.

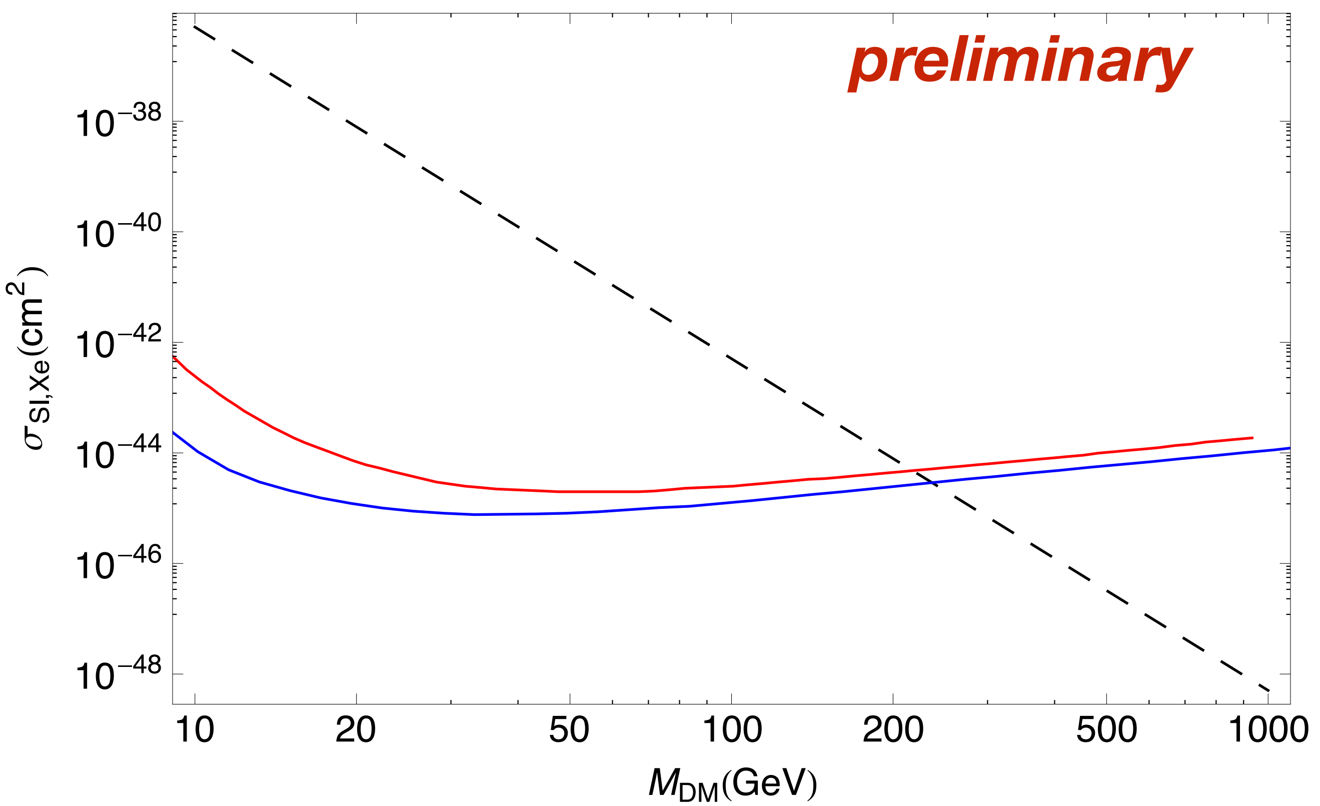
(Pospelov and ter Veldhuis, PLB 480, 181 (2000))

$$\sigma_n = \frac{144\pi}{25}\frac{m_n^2}{A^2}\frac{Z^4\alpha^2}{37.0\ \mathrm{GeV}^{-2}}\left(4\pi\frac{0.135}{m_D^3}\right)^2 \left(0.3894\times 10^{-27}\ \mathrm{GeV}^2/\mathrm{cm}^2\right).$$

- Potentially large cross section; tight constraint! Very hard to suppress, unlike Higgs couplings, may reliably exclude/discover composite models with EM charges

- Dimensional analysis isn't good enough - lattice calculation!

Xenon100 (red), LUX (blue) vs. QCD−scaled EM pol. (black)



# Direct detection: Higgs exchange

- Higgs couplings for the mass-eigenstate fields:

$$\mathcal{L} \supset (\bar{\psi}_+ \bar{\psi}_-) R^{-1}(\theta) \begin{pmatrix} 0 & yh \\ yh & 0 \end{pmatrix} R(\theta) \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

- Expanding in the small Yukawa limit:

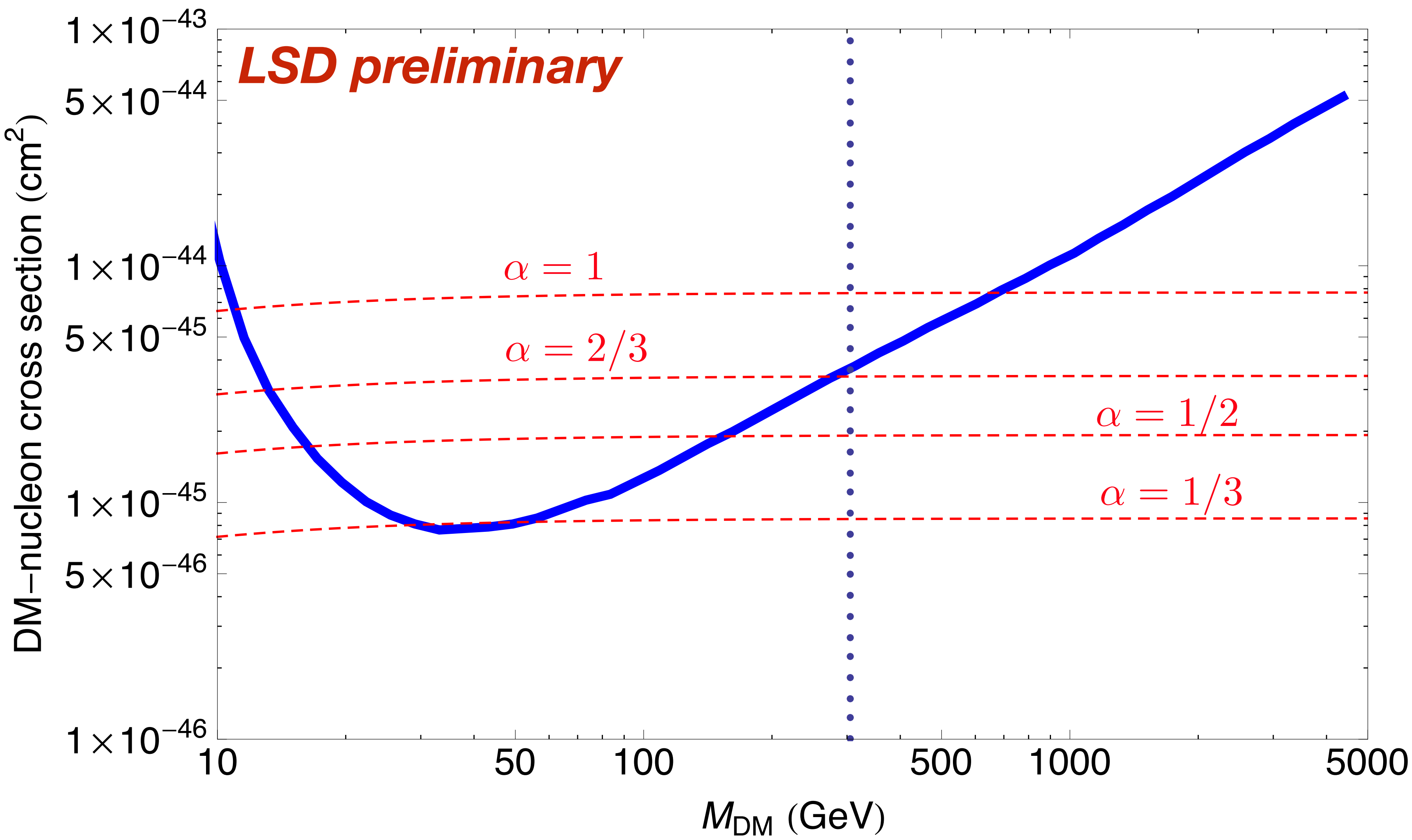
$$\mathcal{L} \supset h \left[ \frac{2y^2 v}{\Delta} (\bar{\psi}_+ \psi_+ - \bar{\psi}_- \psi_-) + 2y \bar{\psi}_+ \psi_- - \frac{2y^3 v^2}{\Delta^2} \bar{\psi}_- \psi_+ \right]$$

- Note the FCNC-type terms! No impact on direct detection, however; contributes only to double-H exchange (or possibly inelastic scattering?)

- We can calculate Higgs-fermion couplings, but interested in coupling to baryons! As in QCD, we need the "sigma term" (extract from our spectrum):

$$\sigma_f = m_f \langle B | \bar{\psi}_f \psi_f | B \rangle = m_f \frac{\partial M_B}{\partial m_f}$$

# Direct detection: Higgs exchange, continued



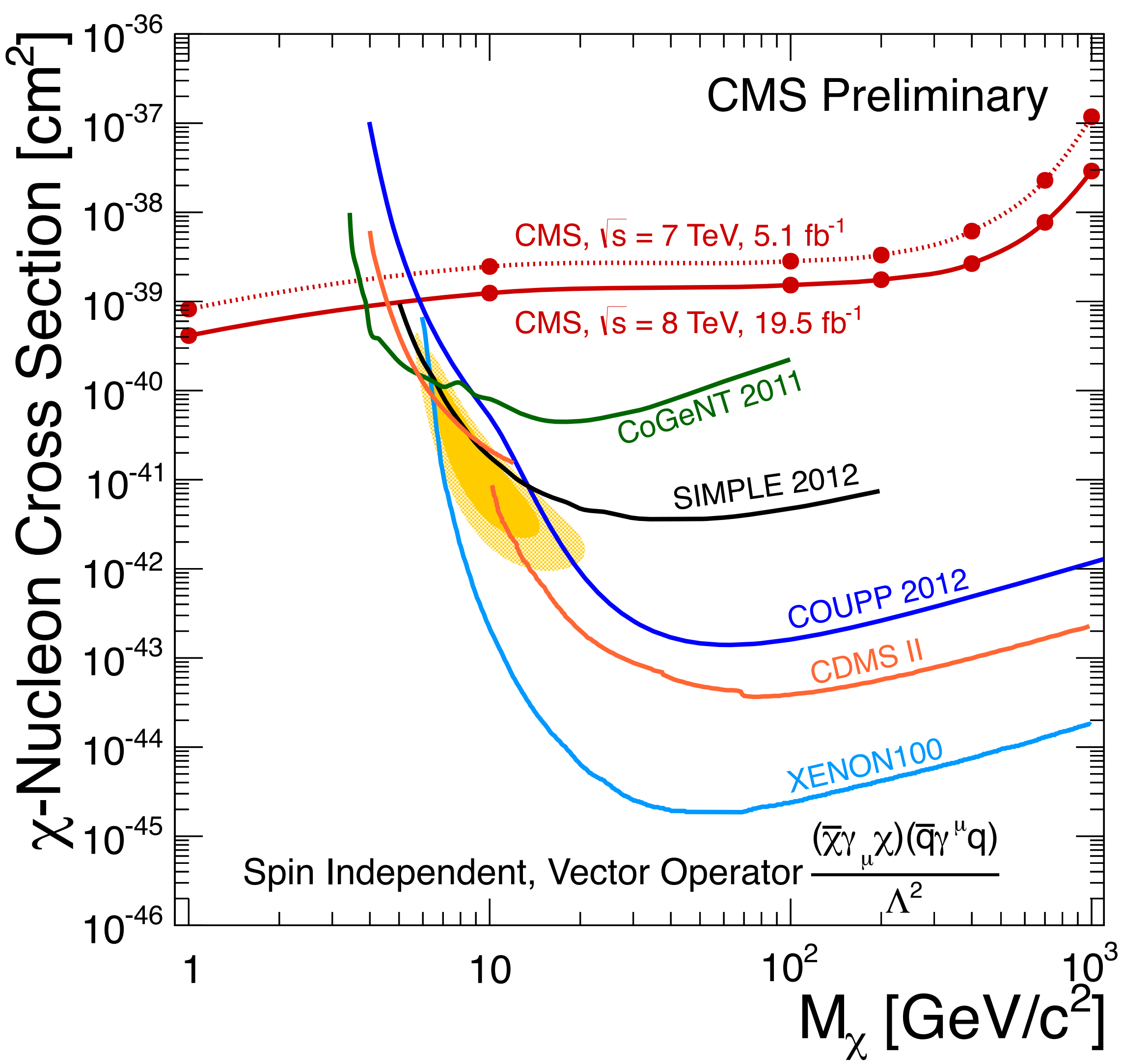

$$\sigma = \frac{\mu(m_B, m_h)^2}{4\pi A^2 m_h^4}(Zf_p + (A-Z)f_n)^2 \times g_h^2$$

$$g_h = \left[\frac{yh}{m_f}\frac{\partial m_f}{\partial(yh)}\right]_{h=v}\left[\frac{m_f}{M_B}\frac{\partial M_B}{\partial m_f}\right]$$

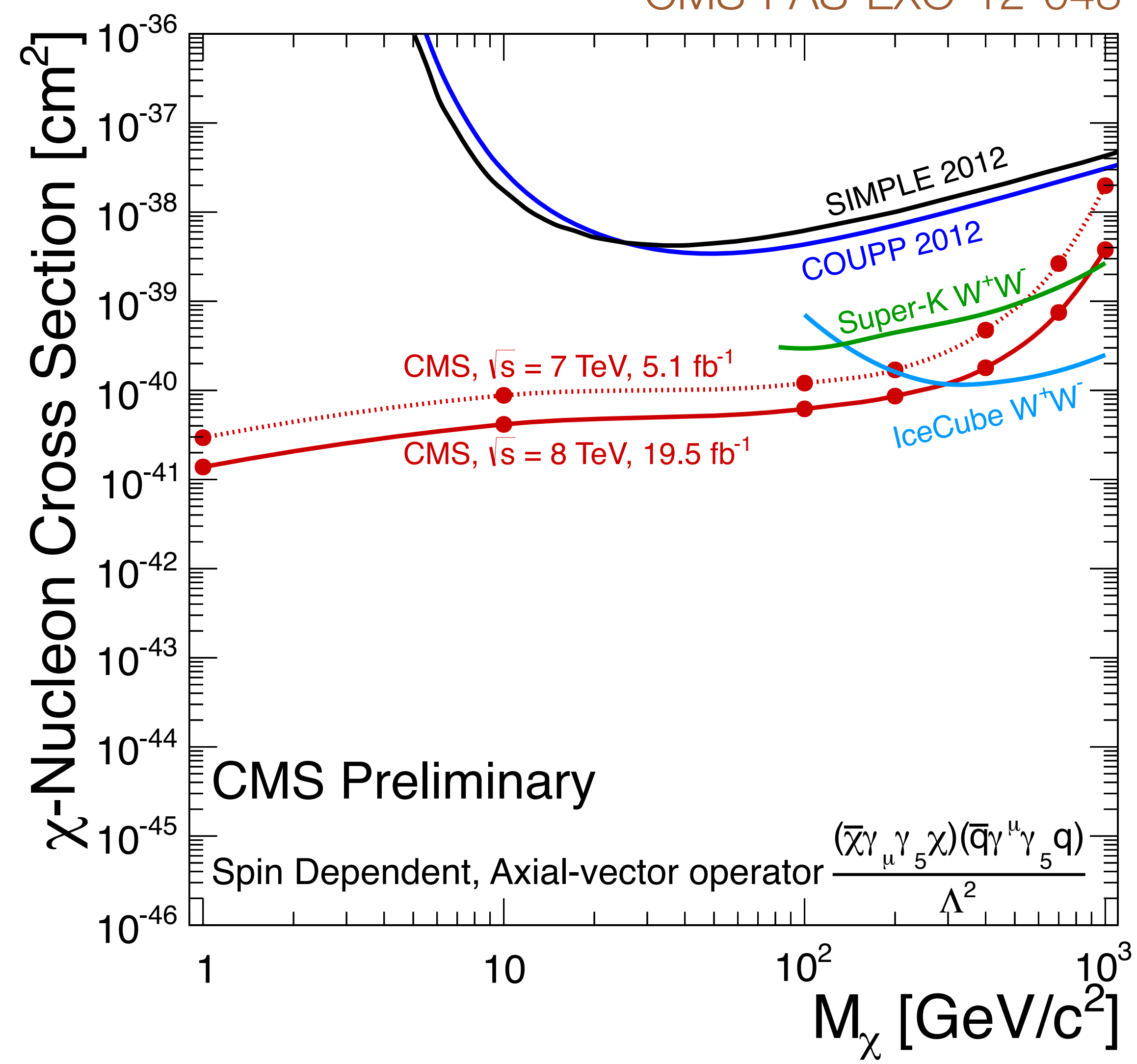
$$\alpha \approx \frac{2(yv)^2}{\bar{M}\Delta}$$

# Collider studies

- Mesons are at least half as light as the baryons, so if we're looking in a collider we'll find those first, except for unusual circumstances.
- Baryons are in principle constrained by standard missing-energy collider DM searches, e.g. monojet:




CMS-PAS-EXO-12-048

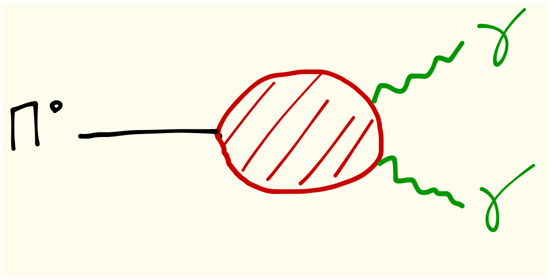


# Meson decay

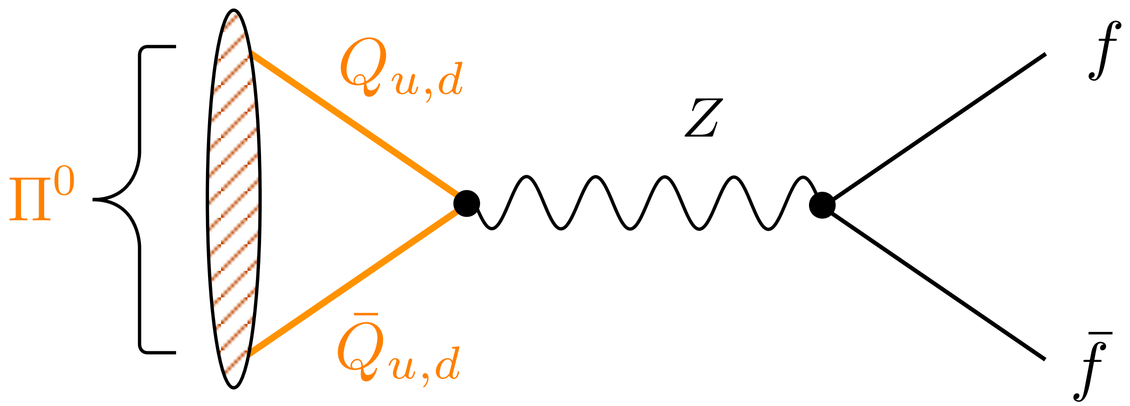
- Some lessons from previous work on SU(2) composite DM still apply here for meson production and decay

- Charge assignment gives cancellation in axial anomaly diagram - decay to photons is suppressed!

$$\Gamma(\Pi^0 \to \gamma\gamma) = \left(\frac{\alpha}{\pi F_\Pi}\frac{M^2}{16\pi^2 F_\Pi^2}\right)^2 \frac{M^3}{64\pi} = \frac{\alpha^2 M^7}{2^{14}\pi^7 F_\Pi^6}$$



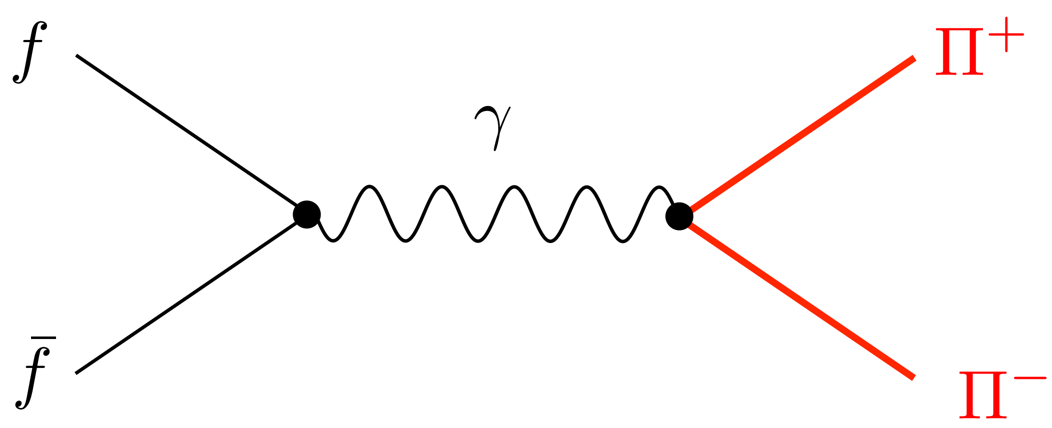

- Opposite scaling for decay to fermions, mass flip in final state gives preferred decay to heaviest SM states

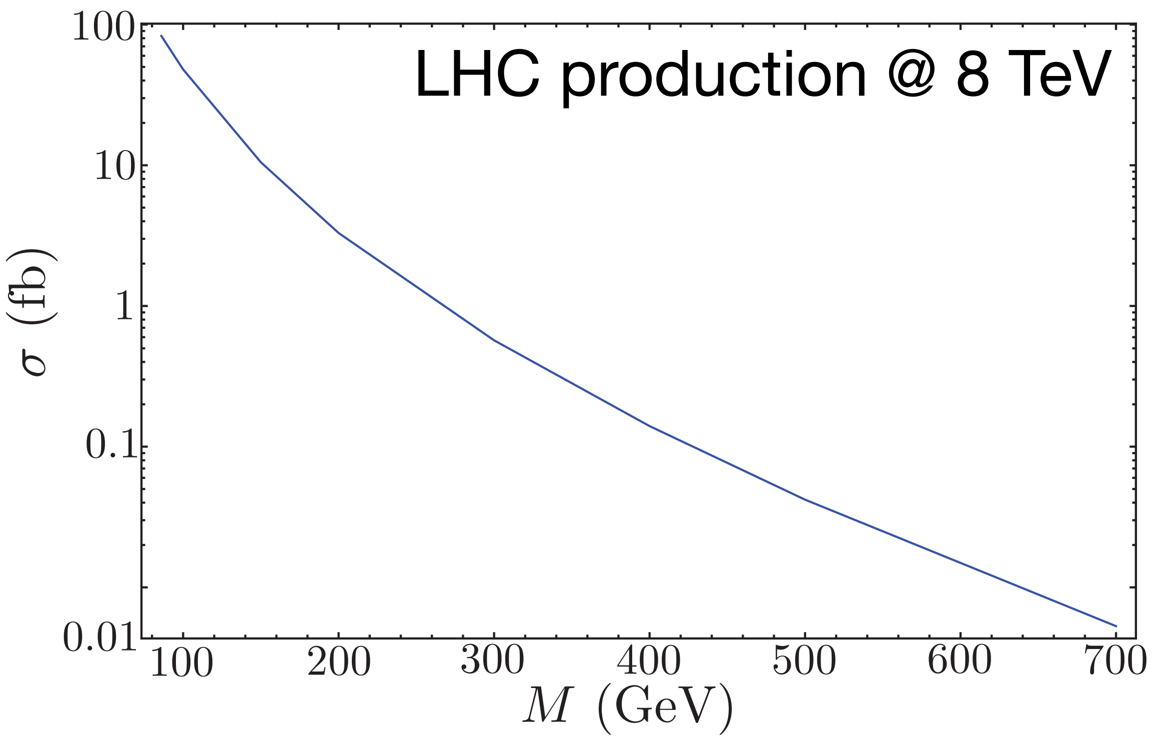



$$\Gamma(\Pi^0 \to Z^* \to f\bar{f}) = N_c \frac{G_F^2 \sin^4\theta_W Q_Z^2 F_\Pi^2 m_f^2 (M^2 - m_f^2)}{8\pi M}\left(\frac{m_Z^2}{M^2 - m_Z^2}\right)^2$$

# Meson production and collider bounds

- Charged "pions" can be made in colliders through Drell-Yan production
- Strong bound from LEP: M >~ 90 GeV.
- Mass flip in decay leads to top-bottom resonance pair production - no dedicated searches, but some constraint from final states with many b's



# Indirect detection: fireballs and gamma rays

- With thermal origin or dark nucleon oscillation, can have an indirect gamma-ray signal from DM annihilation!

- Expected to be quite complicated…e.g. QCD annihilation at low momentum gives many-pion final states.  Further study needed here…

**Proton-antiproton annihilation and meson spectroscopy with the Crystal Barrel**

Claude Amsler

*Physik-Institut der Universität Zürich, CH-8057 Zürich, Switzerland*

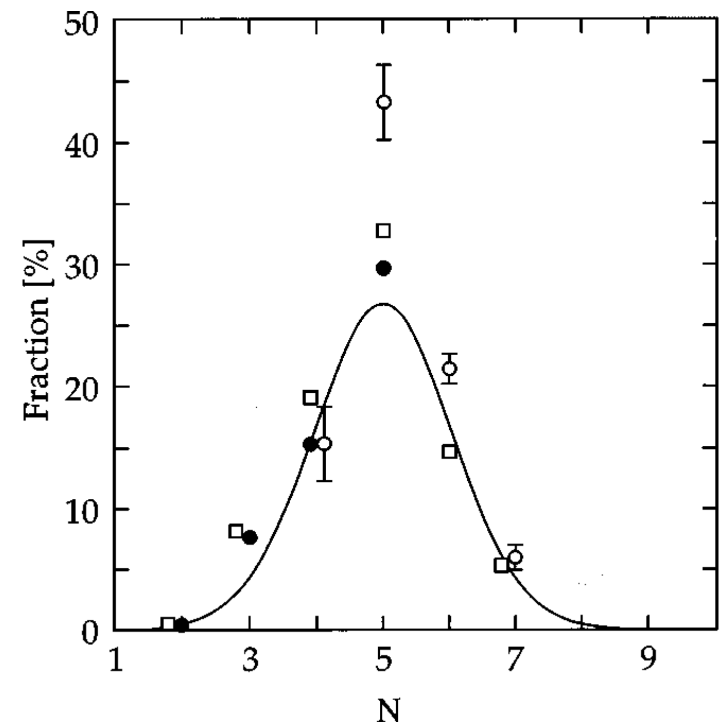
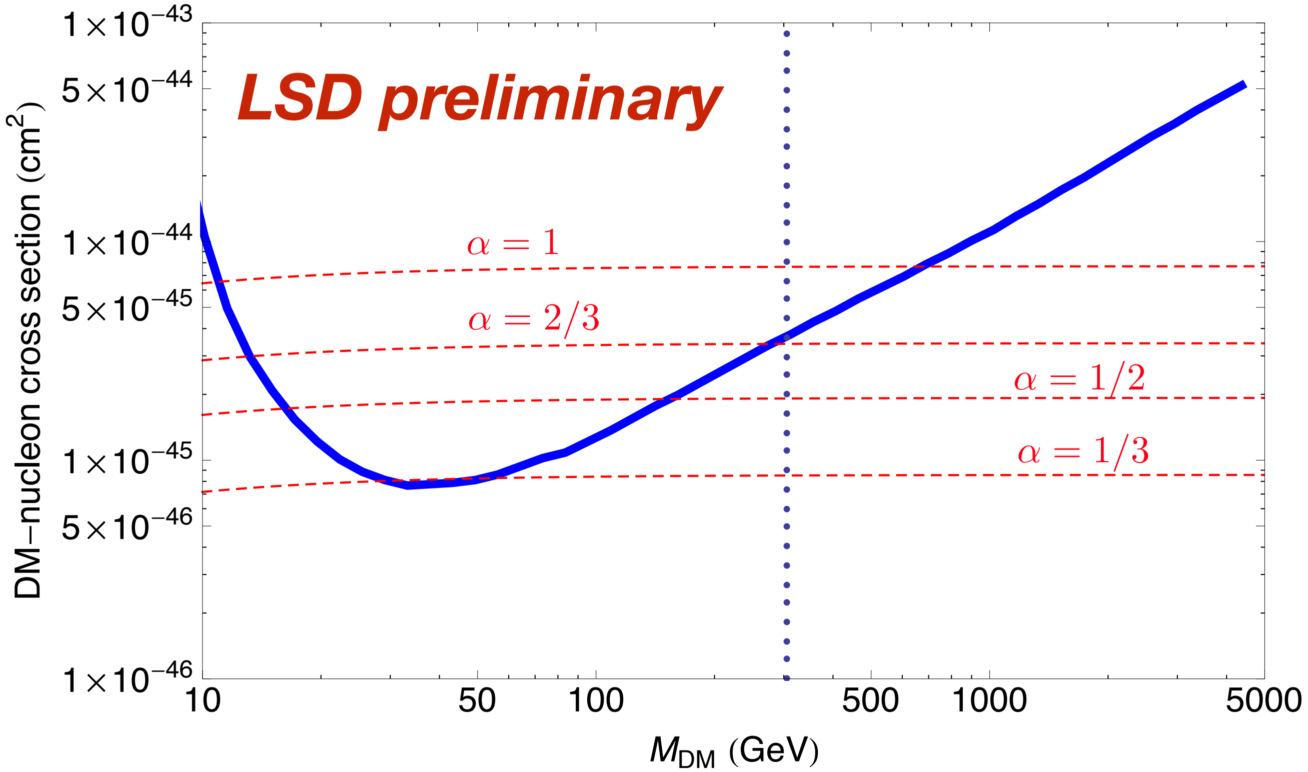
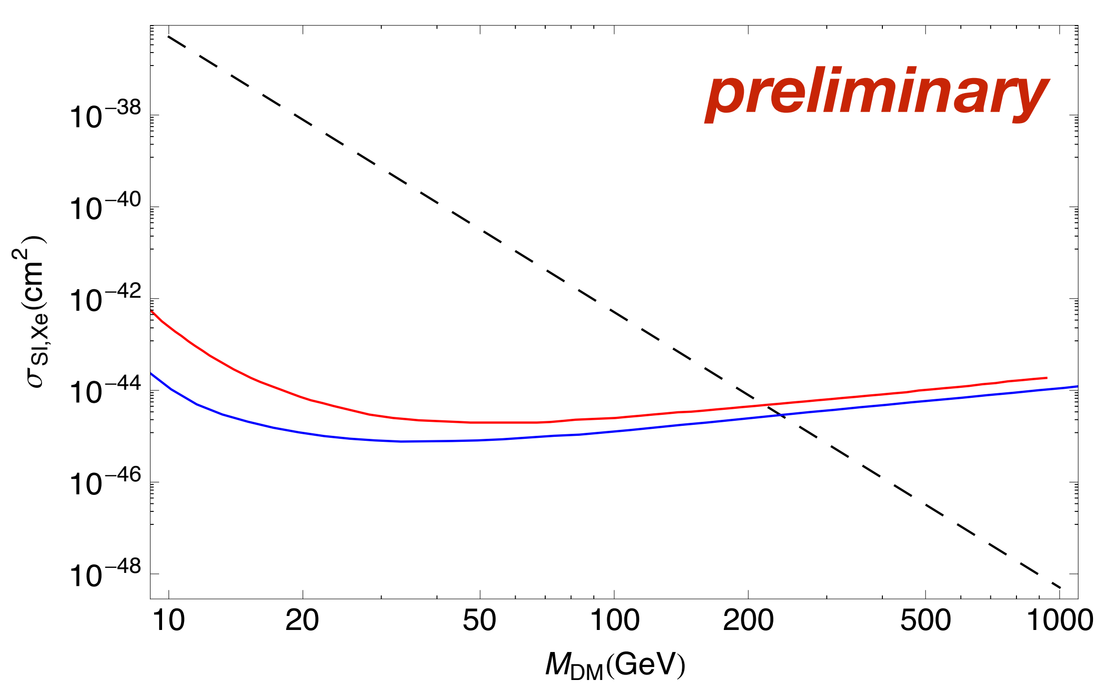



FIG. 1. Pion multiplicity distribution for $\bar{p}p$ annihilation at rest in liquid hydrogen: □, statistical distribution; ●, data; ○, estimates from Ghesquière (1974). The curve is a Gaussian fit assuming $\langle N \rangle = 5$.

# Summary

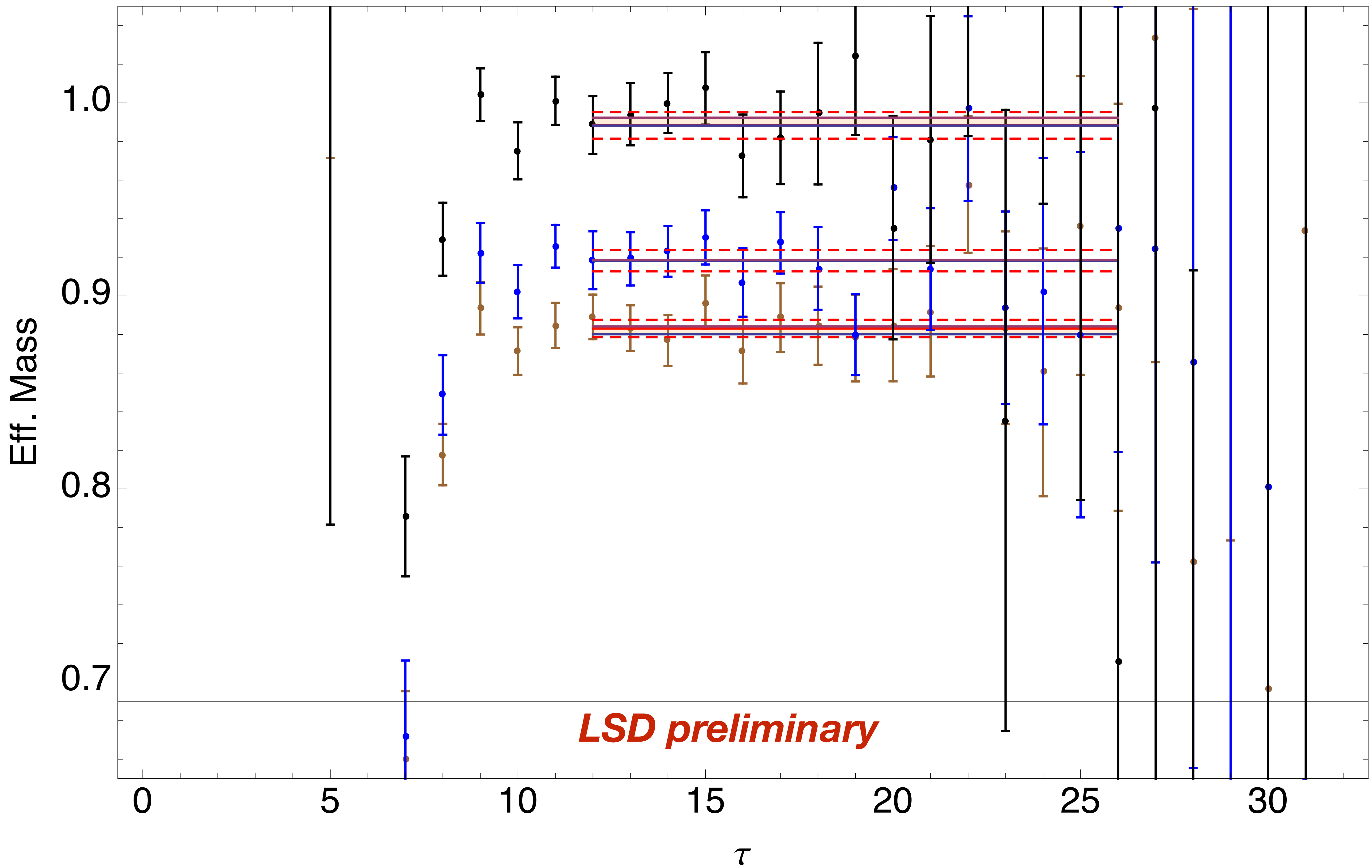
- Growing motivation from astrophysics for study of composite DM. Lattice techniques are maturing enough to rigorously explore these strongly-coupled theories!
- SU(4) simple model with interesting features presented. First calculation of spectrum, coupling to Higgs boson for direct detection.
- Next steps with SU(4): EM polarizability, mass splitting, check quenching error.
- Future directions: study vacuum alignment, careful construction of relic density, self-interactions, …
- Pure speculation: glueball DM on lattice? (model by M. Poseplov)



# Backup slides

# SU(4) baryon effective mass



# Measurement of antineutron-proton total and annihilation cross sections from 100 to 500 MeV/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